Radiation biology – An important science for an advanced nuclear nation like South Africa

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The sustainability of radiation biology (radiobiology) is under threat in South Africa because of underdevelopment in the discipline, despite the fact that South Africa has been a user of radiation since radioactivity and X-rays were discovered. The widespread use of radiation in medicine, nuclear reactors, particle accelerators and other sophisticated nuclear facilities in South Africa makes it imperative that the interaction of radiation with biological systems is understood. For example, radiobiology is critical in radiation oncology and cancer treatment. Radiobiology is a distinctly biological science and its uniqueness and value should be highlighted to provide insight for authorities and other relevant parties. Regrettably, radiobiology has been largely neglected despite the importance of maintaining expertise and competence in this discipline. Many radiation-associated disciplines require radiobiology for their training and practice yet few radiobiologists are available nationally. The scientific community needs to be informed of the predicament of radiobiology in South Africa so that the situation can be addressed. Radiobiology is a scarce skill that needs to be developed to support South Africa's mature radiation infrastructure. The country has too few radiobiologist training programmes and there is a lack of succession planning. Radiobiology is required for training and practice in a number of disciplines that use radiation, but, as a result of a shortage of qualified personnel, teaching of radiobiology has frequently been conducted by non-experts. To reinvigorate radiobiology in South Africa, a collective effort by government, academia, industry and allied professionals is required.

Introduction

South Africa is a developing country with an advanced nuclear industry, yet some radiation sciences, particularly those in the Life Sciences domain, are severely underdeveloped. Despite exposure of humans to ionising radiation in the nuclear industry, in mining and in medicine, the country currently functions in most centres without radiation biologists. Radiobiology is the discipline dedicated to the understanding of effects of radiation in living systems. This branch of science is essential, yet it is poorly developed and under-represented in South Africa.

Ionising radiation is extremely useful in many spheres that contribute to human health and the economy. Thus, it is appropriate in a modern, technologically driven country like South Africa to use radiation technology. It is also important, therefore, to maintain competence in the radiation sciences, including radiobiology, to ensure the effective and safe use of radiation. In medicine, radiation is extensively used in radiological procedures and more than half of all cancer patients in South Africa receive some form of radiotherapy. In addition, the country has nuclear power and a sophisticated nuclear industry served by a considerable number of personnel. It is, therefore, reasonable and desirable for the biological aspects of radiation, in addition to the physical radiation sciences, to be comprehensively addressed.

Radiobiology, as a science, has a major role to play in radiation research and academic development of the radiation sciences. Radiobiologists also have a critical role in training radiation workers in the various radiation-related disciplines, particularly in radiation oncology, which requires a good understanding of radiobiology. However, the number of radiobiologists in South Africa and worldwide is dwindling and has become too small to meet demand. Initiatives need to be started urgently to develop radiobiology and to increase the number of specialist radiobiologists in South Africa.

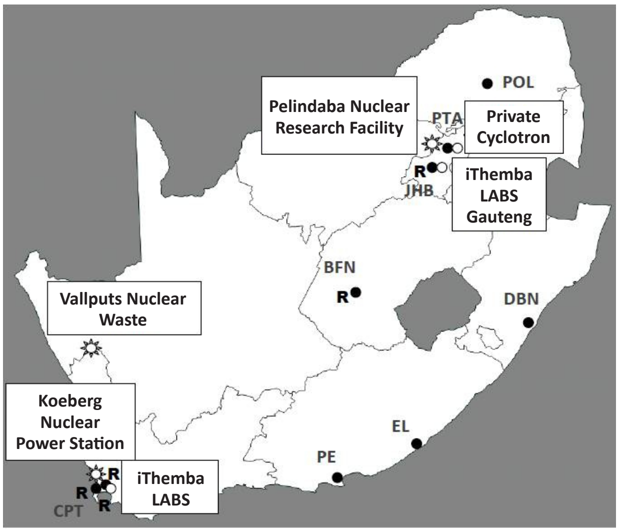
A brief history and overview of radiation technology in South Africa

Given South Africa's long history of radiation usage, it is surprising that radiobiology, as a discipline, has not been developed more. South Africa has been a user of radiation since radioactivity and X-rays were discovered. To provide some background to the country's experience with radiation spanning more than a century, an overview of radiation usage in South Africa is provided. The geographical locations of some of the major centres mentioned are shown in Figure 1.

Radiation medicine

Within a year of the discovery of X-rays in 1895 by German physicist Wilhelm Conrad Röntgen, basic X-ray apparatus was being operated in South Africa.[1] During the Anglo–Boer War (1899–1902), several X-ray units were in service in the country,[2] putting the nation at the forefront of medical diagnostic radiation usage at the time.

It was soon discovered that X-rays could induce biological effects in tissue and it was not long before their application in the treatment of cancer became apparent. South Africa, once again, was quick to absorb the new technology and radium tubes were imported for this purpose as early as 1904.[3] In addition to radium treatments, X-ray machines were developed specifically for radiotherapy. Initial limitations were as a result of poor beam penetration into the body with the result that only superficial tumours could be treated effectively. After many years of use of these poorly penetrating X-ray machines, which often yielded severe skin reactions, the first megavoltage therapy units were introduced. These higher energy machines allowed effective treatment of deep-seated tumours. Cobalt units for radiotherapy were installed in South African radiotherapy departments in the late 1950s,[3] less than 10 years after the first cobalt treatments, which were delivered in Canada in 1951.[4] Subsequently, linear accelerators were introduced in South Africa in the 1970s.[3] Today, IMRT (Intensity Modulated Radiotherapy) is common, with some centres now using the most modern image-guided radiotherapy equipment.



Source: Map background courtesy of Daniel Dalet and d-maps (http://d-maps.com/carte.php?lib=south_africa_map&num_car=11688&lang=en)
CPT, Cape Town; BFN, Bloemfontein; JHB, Johannesburg; PTA, Pretoria; EL, East London; PE, Port Elizabeth; DBN, Durban; POL, Polokwane.
R, presence of radiobiology; ●, radiation oncology training facilities; ○, represent particle accelerators; sun symbols indicate nuclear facilities or waste sites.

FIGURE 1: Location of centres of radiobiology within the South African radiation landscape.

Specialised radioactive implant treatments (brachytherapy) for specific sites including prostate, breast, eye and gynaecological tumours are also commonly employed.

Several particle accelerators have been developed in the country over the past 50 years and a number of cyclotrons are now in operation. The 1980s saw the development of particle radiotherapy at Faure near Cape Town with the building of the cyclotron at the National Accelerator Centre, now called the iThemba Laboratory for Accelerator-Based Sciences (iThemba LABS). Neutron and proton particle beams are available at this facility for treatment of cancer patients. In addition, research in several radiation sciences, including radiobiology, as well as isotope production, are undertaken at iThemba LABS.

Each stage of the evolution of diagnostic radiology and radiotherapy has appeared in South Africa since the discovery of X-rays and radioactivity, with well-developed infrastructure now present in all main centres. Nuclear medicine is no exception. Nuclear medicine was first conducted in South Africa in 1948 in Pretoria using imported isotopes,[5] and local accelerator-produced nuclides have been produced since 1955.[5] Both SPECT (single photon emission computed tomography) and PET (positron emission tomography) imaging and hybrid imaging techniques, as well as therapeutic nuclear medicine, are now available in major South African cities.

When considering radiobiological effects in humans, medical radiation is by far the largest contributor to radiation exposure from human made sources.[6] Radiotherapy is a mainstay of cancer treatment with more than half of all South African cancer patients requiring some form of radiotherapy during their treatment.[7] Whilst radiotherapy delivers large cytotoxic doses of radiation to individuals during tumour treatment, imaging using ionising radiation is the fastest growing source of radiation exposure[8] and population risk. Notably, CT (computed tomography) scanning, notwithstanding its great benefits to diagnosis, is one of the major contributors to radiation dose and its associated carcinogenic risk to the population at large.[8] The invention of the CT scan was remarkably a South African contribution to medical imaging. The South African radiation scientist Allan Cormack, was awarded the Nobel Prize for Physiology or Medicine, together with Godfrey Hounsfield, in 1979 for conception of the CT scanner. The original concept was developed by Cormack while working at the University of Cape Town at Groote Schuur Hospital.[9]

Nuclear industry

South Africa has an established nuclear industry, which is strong in the radiation physics and nuclear engineering sciences in terms of training and professionals in service, but also suffers from a lack of development in radiobiology. Nevertheless, the local nuclear industry has an interesting history, which in many ways has mirrored international developments as South Africa's radiation technology has progressed with advances in global knowledge.

South Africa's nuclear industry originated in the 1940s with the creation of the Uranium Committee, and then later the Atomic Energy Board, and has been evolving and developing until the present day. South Africa's nuclear weapons programme was developed under the apartheid government during the 1970s and then voluntarily dismantled in the 1990s.[10] In 1999, a parastatal, the Nuclear Energy Corporation of South Africa (NECSA), was instituted. Its role is to undertake research and development of peaceful uses of nuclear energy and radiation science and to process nuclear material.[10] NECSA operates the Safari-1 nuclear research reactor at Pelindaba, which is situated approximately 30 km west of Pretoria (Figure 1). The Vaalputs nuclear waste site situated approximately 600 km north of Cape Town (Figure 1) is also managed by NECSA.[11] NECSA's subsidiary, NTP Radioisotopes, is a leading international supplier of radioisotopes and radiopharmaceuticals. They are currently the world's largest supplier of molybdenum-99,[10] a precursor of technecium-99, which is used extensively in nuclear medicine departments around the world.

South Africa also uses nuclear fuel as a source of energy. Approximately 5% of the country's electricity comes from nuclear power[10] generated at the Koeberg Nuclear Power station near Cape Town (Figure 1), which has been in operation since 1985. There are plans for additional power reactors in the country.[12]

Other sources of radiation

Mining, which has played a significant role in the South African economy for over 100 years, is a notable source of radiation exposure because of the radioactive materials found in the earth. South Africa is a major producer of uranium, which is largely a by-product of gold and copper mining. As a result, radioactivity in and around mines is often considerable. Indeed, radiation from mining operations may have an impact on the health of mine workers and others exposed to mine waste.[13] As a consequence, the mining industry, which is a major employer, has been acutely aware of radiation hazards and the management thereof, and thus has had a large vested interest in radiation protection. As a result of mining operations, human exposure from radioactive mine waste dumps requires monitoring. Monitoring is one of the roles of the National Nuclear Regulator. A recent report in local newspapers described how radioactivity levels of mine dumps in certain areas adjacent to human populations in Gauteng may approach levels similar to those found at Chernobyl.[14]

Overview of radiobiology as a discipline

Radiobiology – A distinctly biological science

Whilst radiobiology may sometimes be associated with radiation protection and monitoring, radiobiology is a distinctly *biological* science that seeks to understand the specific interactions of radiation with living systems, while borrowing from cell and cancer biology, physiology and, more recently, molecular biology. Radiation has been present since life began and mammalian cells have developed certain capacities to respond and adapt to radiation through damage response cascades, which depend critically on dose rate and how the radiation is fractionated. Although cellular radiation responses resemble the effects of genotoxic drugs, radiation effects in living systems are complex biological processes that are uniquely affected by temporal and spatial factors.

Major applications of radiobiology

In general, radiobiology has two major applications where it is essential that intellectual capital be maintained, (1) the understanding and management of radiobiological risks to human populations and (2) the use of radiotherapy in the treatment of cancer.

Radiobiological risks

The benefits of radiation are well known but radiation usage carries risks. Radiation exposure increases the chance of developing cancer and may induce genetic effects. Both are radiobiological consequences that need to be understood and minimised. In addition, risks to special groups, such as pregnant women and children, have to be considered. Developing tissues and immature organisms tend to be more radiosensitive. For example, the foetus is particularly sensitive to radiation during the first trimester of pregnancy and thus it is important to limit doses during this critical period. Children are more radiosensitive than adults and, therefore, may be at greater risk of radiation effects.

While limits for radiation exposure are prescribed, no exposure is completely safe and there is still some radiobiological uncertainty regarding human response to low doses of radiation. There is good evidence for a dose-effect relationship in the high dose region but it is necessary to extrapolate to estimate the risks at lower dose levels. Thus, there is some doubt as to the true relationship between low doses and the induction of biological effects. Several extrapolation models have been proposed, including the simple linear, the super-linear, linear quadratic and the hormesis models, as well as the possibility of a threshold below which no risk exists.[15] The linear no threshold model is often adopted by regulatory bodies in the interests of conservatism when defining radiation dose limits for human exposure. However, there is much debate as to the most appropriate models to use.[16] It is often assumed that any dose, no matter how small, carries some risk.

On an individual basis, risk from low-dose exposure may often be considered negligible but, when compounded for human populations, may contribute significantly to the number of radiation-induced cancers and genetic effects in the population at large and thus become a public health issue.

Whilst extensive use of medical radiation contributes to significant population exposures in everyday life, radiation can also affect human lives in times of accidental exposure or during natural disasters. The 2011 tsunami disaster at the Fukushima nuclear power station in Japan has highlighted the need for radiation preparedness and an understanding of the biological consequences of radiation. With extensive use of radiation, despite extensive safety measures being in place, accidents can and do happen. Recently, in South Africa, 91 workers at Koeberg nuclear power station were contaminated with radioactive material whilst performing maintenance.[17] Fortunately, the exposure levels were fairly low but such incidents do highlight the need for radiobiological collaboration in radiation safety planning, assessment and response to radiation accidents.

Radiotherapy

It is important to maintain expertise in the fundamental sciences of radiation oncology in order to preserve intellectual capacity and effectiveness in this area. Radiobiological effects induced by radiotherapy need to be understood and modified for the benefit of cancer patients. Radiotherapy for cancer exploits radiobiological principles to create a therapeutic advantage, that is, to maximise the amount of tumour damage whilst minimising the amount of healthy tissue affected. A sound knowledge of radiobiology should thus be a prerequisite for anyone working in radiotherapy.

Radiobiology is important for radiation oncology research and practice. A detailed discussion of research areas in radiobiology is beyond the scope of this article, but an overview is provided in Table 1. Subjects range from the basic interactions of radiation with cells and tissues to the applied use of radiotherapy in the treatment of cancer.

Radiobiology in South Africa

Some South African scientists who have made significant contributions to radiobiology internationally are featured in Box 1.

Development opportunities for radiobiology in South Africa

Research, training and service in radiobiology have great potential for development in South Africa. Each of these aspects is important for the country to develop expertise for support of South Africa's significant radiation establishment. There are many aspects of radiobiology in South Africa that make it both challenging and unique. While many specifically South African problems can be addressed, many issues in radiobiology are universal and it is important to encourage research into diverse areas.

With the increasing burden in Africa of non-communicable diseases such as cancer, radiotherapy will become increasingly relevant. It is thus important that some resources are directed towards South Africa's own unique problems in this area. For example, compared with the developed world, many cancer patients in South Africa are diagnosed with advanced tumours, which may present particular radiobiological challenges. In addition, South Africa's burden of infectious agents, such as HIV and human papillomavirus, may influence patient susceptibility to disease and response to therapy.

TABLE 1: Overview of key areas of research in radiobiology – the science that studies the effects of ionising radiation on living systems.

Topics in radiobiology	Key areas of research
Radiation damage response	Apoptosis resistance in tumours, radiosensitivity,[58] bystander effects[59]
Fractionation and tumour kinetics	Tumour repopulation,[60] fraction size
Normal tissue tolerance	Tissue kinetics and architecture, volume effects
Biological equivalence estimation	Modelling, treatment design, treatment alteration and errors
Stem cells	Tumour[61,62] and normal tissue[63]
Tumour microenvironment	Blood supply, hypoxia-induced radioresistance, general therapeutic resistance
Functional imaging	Tumour microregions[64] (hypoxia,[65] metabolism,[66] proliferation,[67] angiogenesis[68])
Tumour metabolism	Glycolytic phenotype of tumours,[69] metabolic targeting[70]
Tumour-specific markers	Tumour-specific antibodies,[71] radioimmunotherapy
Chemical modifiers	Radiosensitisers and radioprotectors
Radiation modality	Radiobiological properties of different radiation modalities
Predictive testing	Biology-based treatments
HIV and radiosensitivity	Enhanced radiosensitivity of HIV-infected persons[19]
Biological dosimetry	Cytogenetic damage from accidental radiation exposure[72]
Insect control	Malaria,[73] agriculture
Radiation carcinogenesis	Radiation medicine,[74] radiation protection

Note: Please see the full reference list of the article, Hunter A. Radiation biology – An important science for an advanced nuclear nation like South Africa. S Afr J Sci. 2012;108(5/6), Art. #972, 10 pages. http://dx.doi.org/10.4102/sajs.v108i5/6.972, for more information.

BOX 1: South Africans who have made a significant international contribution to radiobiology.

Lionel Cohen (1918–1999)

In the 1950s, Lionel Cohen, of the University of the Witwatersrand, conducted important early radiobiological experiments at the Experimental Oncology Laboratory at Johannesburg Hospital[52] to define the relationship between fractionation and total dose for an isoeffect after radiotherapy, as well as other laboratory studies on radiosensitivity. He went on to have a distinguished career in the USA, later heading up the experimental neutron radiotherapy programme at the Fermilab clinical therapy facility near Chicago.[53]

Tikvah Alper (1909–1995)

Tikvah Alper[54] was born in Cape Town and educated at the University of Cape Town, obtaining her degree in 1929. Alper had an outstanding career in radiobiology, working at the Gray Laboratory of the Hammersmith Hospital in London and at Cambridge with Douglas Lea, who had demonstrated in 1930 the first ever radiation survival curves for bacteria. Early in Alper's career, having demonstrated her abilities, she was made head of Biophysics at the South African National Physics Laboratory but was forced to leave in 1951 because of her outspoken opposition to apartheid. Thereafter, she immigrated to the UK and pursued an illustrious career in radiobiology, serving time at, and later becoming director of, the MRC Experimental Radiopathology Research Unit at Hammersmith Hospital in London. Drawing on her considerable experience, she wrote the classic radiobiology text, *Cellular Radiobiology.*[55] Her greatest fame, however, stemmed from her work in 1960 in which she irradiated scrapie – which is responsible for bovine spongiform encephalopathy or 'mad cow disease'. On the basis of her findings, she hypothesised in a letter to *Nature* that the infectious agent was not composed of nucleic acid.[56] Only in the 1980s was the infectious agent characterised and shown to be a prion.

Dudley Goodhead

Dudley Goodhead, who was also born and educated in South Africa, was awarded the 15th Gray Medal in August 2011 for his outstanding contributions to the field of basic radiation science.[57] Originally trained as a physicist, he soon 'saw the light' and moved into radiobiology where he made significant contributions to the understanding of radiation track structure and its implications for radiobiological effects. He was Director of the Medical Research Council's Radiation and Genome Stability Unit at Harwell, UK and has also served on several renowned international committees that assess radiation risks. In 2002, he was awarded the OBE for services to medical research in the UK.

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An understanding of the radiobiology of HIV and HIV-infected individuals is an area that presents an opportunity to make a contribution to the treatment of South Africans and others, particularly in Africa, who also are significantly affected by HIV. The high incidence of people with HIV (approximately 5.5 million South Africans in 2009[18]) means that many people in the country that are exposed to radiation also carry HIV, which has been reported to affect radiosensitivity.[19] Many people are also receiving antiretroviral therapy, which extends the lives of HIV-infected people, but which may also influence their radiation sensitivity. The implications for public health and radiation therapy are potentially large, as most radiation guidelines are based on international evidence-based protocols that were developed in populations that are largely free of HIV.

Another challenge facing radiobiologists in South Africa concerns radiobiology services in clinical radiotherapy departments. Radiobiologists can provide valuable input into treatment design and modification, as well as advice in a range of scientific aspects of clinical radiobiology. For example, treatment delays and interruptions frequently occur in South African radiation oncology centres. Long treatment waiting lists, poor patient compliance and interruptions for medical reasons as well as machine breakdown may compromise the success of radiotherapy, because extended treatments may allow, and even stimulate, tumour cell proliferation. Radiobiologists can provide solutions that compensate for treatment gaps and give advice about treatment protocols and tissue reactions. However, few South African radiation oncology departments have access to radiobiologists. Clinical radiobiology is a key area for development in South Africa, as well as in neighbouring states, where radiation oncology is expanding.

The importance of developing scientific competence in radiobiology

As with any discipline, experts are an important part of a nation's economy and welfare. It is therefore imperative that expertise in radiation science, including radiobiology, is developed and nurtured. The ability to make informed decisions, weigh up risks and design new approaches requires a certain level of sophistication, especially when it comes to radiation.

It would seem logical, given South Africa's large radiation infrastructure, that there should be significant resources channelled into radiobiology as a basic science. The major universities should support radiobiology programmes to develop and maintain intellectual competence in the discipline. Yet this has not been the case. To some extent, radiobiology remains an orphan discipline which has failed to achieve a critical mass, yet is of immense relevance to a modern radiation-consuming society like South Africa. The number of radiobiologists currently employed in South Africa is at a critical level (Table 2) with approximately half within 10 years of retirement. This situation is unsustainable and needs to be addressed urgently.

The introduction of radiobiology sections in radiation oncology departments in the Western Cape Province during the 1980s was associated with the interest in particle radiotherapy at the then National Accelerator Centre at Faure. This initiation of activity in radiobiology was the beginning of a productive period in South African radiobiology history. Radiobiologists from Groote Schuur and Tygerberg Hospitals and the National Accelerator Centre undertook biological calibration experiments and conducted scientific investigations using the latest techniques, which contributed to the clinical utilisation and better understanding of these novel radiation modalities.[20,21,22,23,24,25]

Research and teaching activities were cultivated and, up until 2002, the radiobiological momentum produced over 20 postgraduate degrees from Stellenbosch University and the University of Cape Town, but none have been produced since. During this period, both of these institutions made significant international research contributions to the radiobiology of photons (X-rays and gamma rays) and published notable studies in areas such as dose-modifying drugs,[26,27] repair,[28,29] the oxygen effect,[30,31,32,33,34,35] metabolic modulation,[36] damage response[37,38,39] and biological dosimetry.[40]

Regrettably, after 2000, the cutting of posts and poor prospects for graduates resulted in a sharp decline in radiobiology studies. The three once-thriving laboratories at Groote Schuur Hospital, Tygerberg Hospital and iThemba LABS continue with a much reduced capacity of only five remaining staff members.

Having described a once-vibrant era in radiobiology in the Western Cape followed by a period of contraction, it is fair to state that radiobiology has never been prominent in other regions of the country. Thus, despite pockets of activity nationally, radiobiology has not been well represented in South Africa as a whole. There are, as far as can be determined, no radiobiologists in any other African country.

It is important for South Africa to have scientists and other academics who are active in radiobiology and who can advise on matters pertaining to biological and health effects of radiation. As a scientific discipline, radiobiology both

TABLE 2: The number and locations of radiobiologists in South Africa.

Centre	Number of radiation biologists	Postgraduates in training	Radiobiology research
University of Cape Town/ Groote Schuur Hospital†	2	2	Yes
Stellenbosch University/ Tygerberg Hospital	1	0	Yes
iThemba LABS (National Research Foundation)	1	1	Yes
University of the Witwatersrand/ CM Johannesburg Academic Hospital‡	1	3	Yes
University of the Free State/ National Hospital	1	0	No
University of the Western Cape	0	0	Yes

†, Clinical radiobiologists in South Africa are found only at Groote Schuur Hospital, Cape Town.
‡, The radiobiologist at the University of the Witwatersrand is supported by iThemba LABS.

complements and draws from radiation oncology practice and research. Therefore, whilst radiobiology can exist as a science in its own right, its traditional partner has been cancer therapy, and, consequently, this is where it has found its main niche. An example of such a partnership is evident at Groote Schuur Hospital in Cape Town, where the Radiobiology Section is an integral part of the Department of Radiation Oncology.

Although radiation oncologists study radiobiology during their training, it is important to maintain appropriate depth and expertise in the subject, which can only be properly achieved through maintaining a strong specialist radiobiology presence in radiation oncology departments around the country. This importance is especially relevant for centres that provide radiation oncology training.

There are eight academic training centres for radiation oncology in the country (Figure 1) as well as an expanding private sector, which has grown significantly since the 1997 report of Levin and Goedhals[3] which gave an overview of radiation oncology in South Africa at that time. According to the International Atomic Energy Agency, there are 41 institutions within South Africa that offer radiotherapy.[41] However, despite the extensive therapeutic irradiation of patients, the number of radiobiologists in the country is fewer than 10 (Table 2).

The roles of radiobiology in teaching, research and service to radiation medicine have become a logical fit. In addition to the academic programmes for radiobiologist training (Table 3), radiobiology forms a mandatory part of the curricula of many of the radiation-associated disciplines (Table 4). However, at present, non-radiobiologists frequently teach the subject out of necessity. Research is an important part of any science and is crucial if scientists are to remain current and relevant in their fields. Radiobiology services within clinical departments have also become increasingly necessary, as paradigms for cancer treatment planning are changing. For example, treatments may be optimised by the application of radiobiological models that may be incorporated into treatment prescriptions – such as Normal Tissue Complication Probability and Tumour Cure Probability models. As mentioned previously, others not trained or conversant in radiobiological principles have been inappropriately tasked with advising clinicians. This situation is obviously undesirable. The role of the professional radiobiologist requires specific competencies, as recognised by the Health Professions Council of South Africa (HPCSA), which distinguishes radiation biology as a medical science profession. Radiobiology responsibilities should thus be undertaken by qualified professionals.

Training of radiobiologists

Masters and doctoral studies in radiobiology are offered at the Universities of Cape Town (UCT), Stellenbosch and the Witwatersrand (Table 3). Students have generally been drawn from other disciplines in the Life Sciences. At UCT, an undergraduate course in radiobiology is offered for BSc students and a comprehensive BSc(Med)(Honours) programme in radiobiology is offered in the Faculty of Health Sciences. Entry into the BSc(Med)(Honours) programme requires a major subject in the biological or radiation sciences.

In order to conduct scientific work related to human health or to provide advice that may have an impact on medical decisions, radiobiologists are required to register with the HPCSA. Initial registration as a trainee, formal competence and experiential training are required before full registration and practice as a professional radiobiologist in the medical environment is permitted. Training centres need to be accredited for this role. At present, no radiobiology training centres are accredited by the HPCSA. However, radiobiologists recognise the need for establishing future training and accreditation facilities and this need is currently being addressed by the South African Radiobiology Society (SARS).

For interested parties, a basic syllabus in radiobiology has been compiled by the International Atomic Energy Agency.[42]

Training of radiation oncology registrars (residents)

The training of radiation oncologists is perhaps one of the most crucial roles for radiobiologists. A sound knowledge of radiobiological principles is required to practise radiation oncology and, therefore, radiobiology is a major subject in the training programme of this speciality. (Radiobiology is part of the syllabi of all the radiation medicine specialities.) The College of Medicine of South Africa requires that candidates become proficient in radiobiology as part of their training to achieve their qualifications in radiation oncology, as is the case in other parts of the world.[43] Zeman et al.[44] recommended that a radiobiology programme, in order to satisfy the requirements of the US board exam, should comprise approximately 80% classic and clinical radiobiology and 20% molecular and cancer biology. This requirement is similar

TABLE 3: Training opportunities for radiobiologists in South Africa.

Centre	Undergraduate course	Honours	Masters	Doctorate
University of Cape Town	•	•	•	•
Stellenbosch University	-	-	•	•
University of the Witwatersrand	-	-	•	•
University of the Free State	•	-	-	-

•, present; -, absent.
Although MSc and PhD research dissertations with a radiobiological topic can be conducted at each of the universities indicated, only the University of Cape Town offers degrees specifically in radiobiology. In South Africa, the BSc(Med)(Honours) in radiobiology is equivalent to a 4-year degree.

TABLE 4: Overview of radiobiology training in South Africa.

Radiation biologist on staff (Yes/No)	Academic courses including a radiobiology component								
	Radiation oncology		Nuclear medicine		Radiology		Radiation protection and health physics	Medical physics	Nuclear sciences
	Registrars	Radiotherapy technicians	Registrars	Radiographers	Registrars	Radiographers			
Yes	•	-	•	-	•	-	-	From 2012	-
Yes	•	-	•	-	•	-	-	-	
Yes	-	-	-	-	-	-	-	-	•
Yes	•	-	•	-	•	-	-	•	-
Yes	•	-	•	-	•	-	•	•	-
No	•	•	•	-	•	-	-	-	-
No	•	-	•	-	•	-	-	-	-
No†	-	•	-	-	-	-	-	-	-
No	-	•	-	-	-	-	-	-	-
No	-	•	-	-	-	-	-	-	-
No	-	•	-	-	-	-	-	-	-
No†	-	-	-	-	-	-	-	-	•
No†	-	-	-	-	-	-	•	-	•
No	•	-	•	-	•	-	-	•	-
No	•	-	-	-	•	-	-	-	-

•, presence of specialist; -, absence of specialist.
†, Some centres, despite not having radiobiologists of their own, make use of those from other institutions. In many cases, however, radiobiology academic education is conducted by non-radiobiologists.

to those in South Africa. In the USA, for accreditation of a radiation oncology training institution by the Accreditation Council for Graduate Medical Education, a comprehensive course in radiobiology is mandatory. In addition, the faculty must have a radiobiologist or cancer biologist who has a PhD on their staff to teach radiobiology and cancer biology, and who will provide a 'scholarly environment' for research and teaching.[45] South Africa falls far short of these constraints in most radiation oncology training centres.

Several publications have addressed the issue of radiobiology training for radiation oncologists outside South Africa.[46,47,48] In a recent survey by Rosenstein et al.[49], several conclusions were reached, which may in some ways echo the South African experience. In the USA, there is an aging cohort of radiobiologists (with an average estimated age of 52), who are responsible for passing on radiobiology knowledge. There is a similar trend in South Africa, albeit with a much smaller cohort. It was also noted that there was a disturbing decrease in the proportion of educators specifically trained in radiobiology and that many responsible for teaching radiobiology were not adequately versed in radiation science – only approximately 30% of the group were trained as radiobiologists. Rosenstein et al.[49] recommended, on the basis of their findings, that radiobiology teaching resources be improved and they motivated for new radiobiology graduate programmes. Given that the situation is more extreme in South Africa, it follows that these recommendations should be equally relevant, if not more so, in this country.

While there is a place for short courses in radiobiology for registrars, short courses are not a substitute for proper teaching at the current training centres. Through necessity, because of the dearth of radiobiologists, short courses may be a stop-gap solution, but in the long term it is appropriate for academic centres to develop their own comprehensive radiobiology teaching platforms.

National plans for the advancement of radiobiology

Having considered the significance and relevance of radiobiology, in light of South Africa's extensive current and past radiation usage, it is clear that failure to address radiobiology's status as a scarce skill is detrimental to the country's development. However, this failure can be rectified. In a modern and technologically proficient nation such as South Africa, the importance of radiobiology needs to be promoted and publicised. Not only will the development of radiobiology fulfil current needs, it will also enhance South Africa's capacity and relevance in radiation sciences. Development of radiobiology in South Africa should also contribute to development of the discipline in the rest of Africa, which, as far as can be determined, has no radiobiologists whatsoever. However, it is important for South Africa to 'get its own house in order' first. A significant effort at many levels will be required to stimulate radiobiology and put it on a firm footing. This transformation will require buy-in from government, science councils, universities and those in allied professions. New graduates in the science of radiobiology must be produced and positions for radiobiologists created for these graduates to fill. Recommended courses of action for stakeholders in radiobiology are presented in Table 5.

The national Department of Science and Technology, the Department of Health and the Department of Higher Education and Training have roles to play, as radiobiology is important in the realm of each. Provincial health departments should also play a critical role in the development of radiobiology, which is important in radiation medicine. Science councils, such as the National Research Foundation and Medical Research Council, should recognise the need to develop radiobiologists and help to support and grow the discipline. The Nuclear Technologies in Medicine and the Biosciences Initiative under NECSA has been implemented as a first step to assess the state of the science and to direct

TABLE 5: Recommended actions for stakeholders in radiobiology in South Africa.

Stakeholder	Suggested actions
South African Radiobiology Society (SARS)	• Produce guidelines for radiobiology education, training and practice in South Africa • Engage with other stakeholders to develop radiobiology • Develop accreditation guidelines for HPCSA registration of radiobiologists
Health Professions Council of South Africa (HPCSA)	• Implement a mandatory requirement for radiation oncology training centres to have radiobiologists (or at least for radiobiology training to be undertaken by specialist radiobiologists) in order to be accredited as training centres
South African College of Medicine (CMSA) (College of Radiation Oncology)	• Implement a mandatory requirement for radiobiologists to be on the academic staff at radiation oncology training centres to ensure appropriate training (competence in radiobiology is a requirement of current specialist training)
Nuclear Energy Corporation of South Africa (NECSA)	• Continue to support the Nuclear Technologies in Medicine and the Biosciences Initiative to address scarce skills in radiobiology in collaboration with SARS
Universities (Science and Health Science Faculties)	• Create and develop radiobiology curricula for education of radiobiologists and other radiation-associated disciplines • Employ radiobiologists on faculty
Provincial governments (Health departments and radiation oncology departments)	• Employ radiobiologists in radiation oncology departments • Create trainee positions in radiobiology
Central government (DOH, DST, DOHET)	• Include radiobiology in strategic reports and policy documents concerning health, science and technology, and higher education

DOH, Department of Health; DST, Department of Science and Technology; DOHET, Department of Higher Education and Training.

appropriate actions. However, resources have yet to be allocated to the challenging task of building a sustainable radiobiology infrastructure.

Universities need to embrace and promote radiobiology as an important academic discipline. Academic programmes must be created to train radiobiologists, create expertise and provide quality instruction in the subject for numerous other groups of radiation users. In order to do this, academic positions and laboratories must be created and research programmes initiated. It is reasonable that radiobiological education and training in radiation medicine and medical physics should be offered by specialist radiobiologists and that this condition should ideally become mandatory for accredited training centres.

The malady afflicting radiobiology is not unique to South Africa. The worldwide shortage of radiation scientists has been recognised in the USA and in Germany, where measures are already being taken to rectify this deficit. For example, the National Cancer Institute, which is part of the National Institutes of Health in the USA, is promoting a radiobiology education initiative in collaboration with US and international societies.[50] In Germany, the need for a revitalisation in radiobiology has been recognised under the *kompetenzerhaltung* (maintaining competence) agenda.[51] This agenda has already led to new appointments and the creation of significant research infrastructure by the Bundesministerium fur Forschung und Technologie. Similar initiatives may also be appropriate in South Africa for radiobiology to achieve its own identity and profile in national planning. SARS is the professional society that promotes the interests and standards of the discipline in South Africa. As the representative body, SARS strongly recommends that the development of radiobiology is treated as a matter of national importance and urges politicians and administrators to incorporate the development of radiobiology into their future plans. It is clear that the reinvigoration of the discipline can only be achieved by collective will and effective lobbying and that this will be to the benefit of South African science.

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